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Research Article

A new hybrid psotvac/bfa technique for solving robust placement and tuning of upfc based a new fuzzy multi objective

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ABSTRACT

This paper presents a new Hybrid Particle Swarm optimization with Time Varying Acceleration Coefficients (HPSOTVAC) and Bacteria Foraging Algorithm (BFA) based fuzzy multi-objective methodology for optimal locating and parameter setting of Unified Power Flow Controller (UPFC) in a power system for a long term period. One of the profits obtained by UPFC placement in a transmission network is the reduction in total generation cost due to its ability to change the power flow pattern in the network. Considering this potential, UPFC can be also used to remove or at least mitigate the Congestion in transmission networks. The other issue in a power system is voltage violation which could even render the optimal power flow problem infeasible to be solved. Voltage violation could be also mitigated by proper application of UPFC in a transmission system. These objectives are considered simultaneously in a unified objective function for the proposed optimization algorithm. At first these objectives are fuzzified and designed to be comparable against each other and then they are integrated and introduced to a hybrid method in order to find the solution which maximizes the value of integrated objective function in a three-year planning horizon, considering the load growth. A power injection model is adopted for UPFC. Unlike the most previous works in this field the parameters of UPFC are set for each load level to avoid inconvenient rejection of more optimal solutions. IEEE Reliability Test System (RTS) is used as an illustrative example to show the effectiveness of the proposed method.

Keywords Multi Objective; Hybrid Technique; UPFC; Fuzzy Theory; Voltage Violation.

INTRODUCTION

The fundamental distinctions between the structure of the power systems after the era of restructuring and the conventional structures used before 1990s are mostly due to the socio-economical aspects of power systems rather than technical issues. After the restructuring in electric power systems economics and management, transmission systems are often operated near their different margins. Meanwhile the increasing power demand and competition between market participants necessitate a higher usage of the transmission assets. In such a case the power system will be operated in an unstable or insecure mode. Therefore it is necessary to reinforce the transmission network to meet the new recruitments. More importantly, operation of power market at least near to the competitive equilibrium is one of the most important objectives of the operator, which cannot be achieved with a congested network.

The reactance of network lines, voltage of system buses and line active and reactive power flows in a transmission system can be controlled through the proper application of Flexible AC Transmission Systems (FACTS) devices. Though one of the most important applications of these devices is the system dynamic stabilization, FACTS devices also provide new control facilities in steady state power flow control [1]. In planning phase, the investment on transmission system expansion can be postponed, if FACTS devices are appropriately placed in the network.

The UPFC is a convertor-base controller, which is used for controlling active and/or reactive power-flow through a line as well as the voltage of the bus which the UPFC is located at [1]-[2]. With the ability of controlling the voltage of the UPFC installation bus, this controller is also able to change the voltage pattern in the network and mitigate the voltage violation. Having these all abilities UPFC can be used either simultaneously or selectively to control the active and reactive power flow along the transmission lines of the network [3] to effectively relieve the congestion, reduce the operation cost and meanwhile reduce the expansion cost of the transmission system.

In this paper, a new methodology to solve the complicated problem of finding the optimal location and parameter setting of a Unified Power Flow controller is

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presented. The optimization is aimed at reduction of all the aforementioned difficulties experienced by the system operator which can be overcome by placing and proper parameter setting of the UPFC. Due to the different (or even sometimes opposing) objectives, a proper multi-objective optimization method is necessary to cope with the complexity of the problem.

Since the objectives are not of a same type, (one of them is voltage violation (V) and the others are in the form of cost ($)), at first these objectives are fuzzified and designed to be comparable against each other and then they are integrated and introduced to a hybrid method in order to find the solution which maximizes the value of integrated objective function in a three-year planning horizon, considering the load growth.

UPFC installation cost has not been considered in most of previous studies such as [4]. It is obvious that the economic analysis is not valid ignoring the installation cost. In contrast, this paper considers this cost and especially presents a formulation to calculate the installation cost based on the power injection model of UPFC. The proposed economic model also considers the interest rate and investment recovery in the planning time horizon.

The same UPFC parameters were applied for different load levels of the planning horizon in most of previous works in this area, such as [4]. Unlike these works, the parameters of UPFC are set separately for each load level to avoid inconvenient rejection of some optimal solutions.

The problem model is suited for application of hybrid technique to find the optimal location and parameter setting of UPFC. Particle Swarm Optimization (PSO) is one of the modern heuristic algorithms. The algorithm is based on the social interaction between search agents in feasible search space. Each particle is changing their position and velocity of each individual based on their own previous best position, and the best previous position of their neighbors. Generally, PSO is characterized as an easy concept, easy to implement, and computationally effective [5]. Unlike the other heuristic techniques, PSO has a well-balanced mechanism and flexible to amplify the global and local exploration abilities. However this is possible to occur that PSO converges junior. Recently, this method is used to various fields of power system optimization problem such as reactive power dispatch, voltage control and optimal power flow [6].

Intelligent methods are frequent techniques that can search not only local optimal solutions but also a global optimal solution depending on problem domain and execution time limit. The old optimization methods have the advantage of searching the solution space more thoroughly. The major difficulty is their sensitivity to the choice of parameters. Among intelligent methods, Particle Swarm Optimization with Time Varying Acceleration Coefficients (PSOTVAC) is strong and simple. It requires less computation time and memory. It has also standard values for its parameters.

On the other hand, Bacteria Foraging Algorithm (BFA) which is introduced by Passino [7] as a tool of optimization is a strong algorithm. In this paper, to overcome the problems of the previous techniques, the Hybrid PSOTVAC/BFA is proposed to solve proposed problem in power system. It is also seen that some simple adaptive feature incorporated in the main algorithm makes its convergence even faster. Different studies have been conducted and variety of methods has been proposed for optimal placement and parameter setting of UPFC with different objective functions in the literature. The rest of this section introduces some of the previous studies in this field and also discusses the contributions of the present work that cover the blind spots of the former studies.

The Optimal Power Flow (OPF), which becomes a more complicated problem when including FACTS devices, should be solved as a sub-problem in placement and parameter setting problem. Many methods have been developed to model different FACTS devices in load-flow studies [8]-[9].

Reference [10] applied the augmented Lagrange method to determine the optimal location of the UPFC. Power injection model was used in [11] to propose a hybrid method which incorporates the UPFC in OPF problem. The proposed method found the optimal location of UPFC in order to minimize the generation cost of the system while improving the voltage profile of the network.

Since placing and parameter setting of FACTS devices is a complex, nonlinear, mixed integer and non-convex optimization problem, different heuristic optimization algorithms have been proposed to deal with the complexity of the problem, so a PSOTVAC/BFA-based fuzzy multi-objective approach for locating and parameter setting of UPFC is proposed in present paper. Reference [12] proposed a method for optimal operation of a UPFC installed in a predetermined location. The Genetic Algorithm (GA) was suggested to solve OPF in [8] presence of UPFC and to set its parameters. Though this reference did not propose methodology for optimal placement of the UPFC, the separated parameter setting for different load levels is the interesting aspect of this paper. In fact most of previous works in the realm of UPFC placement planning considered the parameters of UPFC to be fixed at the maximum rated values while the load varies at each bus. As discussed earlier, this may render some of the optimal solutions infeasible due to violation of some constraints such as voltage magnitude limits in some load levels, while in most of the other load levels no violation occurs. In contrast this paper resets the UPFC parameters for each load level to avoid the inconvenience rejection of more optimal solutions.

A fuzzified multi-objective GA based algorithm was proposed in [13] for capacitor placement. Tough the problem was finding the best location of capacitors in distribution networks, the model of objective function and the methodology can be used in UPFC placement problem with some modifications. In the aforementioned study load was not modeled appropriately for a long term period. Similarly in most of studies on UPFC placement, a long term model with load growth has not been considered.

As mentioned so far, a considerable number of studies have been conducted to reduce the cost of generation in power systems. Reduction of voltage deviation in order to reach a more flat voltage profile has been also the subject of many other studies. Congestion management has been the other aim of UPFC placement in the literature. In this paper the reduction of generation cost, congestion mitigation and reduction in voltage deviation are considered simultaneously as the objective functions.

The other virtue of the present work is an adaptive method of finding the proper membership functions in fuzzification process. Fuzzy approach was applied in previous studies such as [13], but membership functions were predefined.

The rest of this paper is organized as follows. An overview of the proposed algorithm is presented in section II. The UPFC power injection model, long-term load model and an introduction of PSOTVAC/BFA algorithm are presented in Section III. The proposed method is presented in section VI. It is tested on IEEE Reliability Test System (RTS) and the simulation results are presented and discussed in section V. The conclusion is drawn in section VI.

II. AN OVERVIEW OF THE PROPOSED ALGORITHM

Before continuing further, this section presents a summarized hierarchical structure of the proposed algorithm as follows. A conceptual flowchart of the proposed algorithm is presented in Fig. 1.

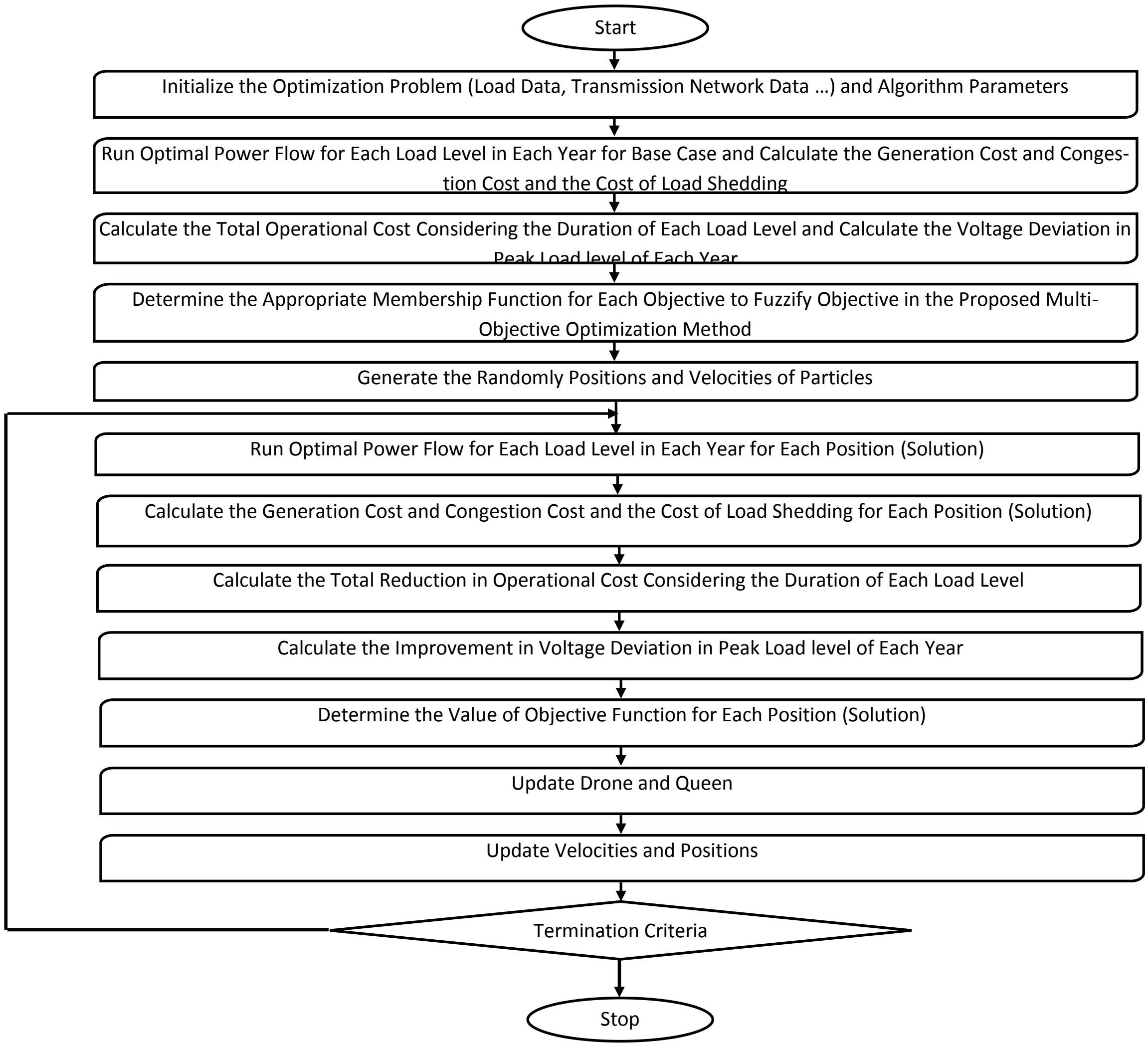

Fig. 1. Conceptual flowchart of the proposed algorithm

1. Run a base case OPF for each load level in each year and calculate the generation and congestion costs. In some load levels the OPF may not be converged. In such a case, let the algorithm curtail the load at some buses and add the cost of load shedding to the generation cost. This simply models the reduction in transmission expansion cost as a result of UPFC placement in our formulation. Find the total cost considering the duration of each load level. Calculate the voltage deviation in peak load level of each year using the formulation presented in subsection VI.2.2.

2. Solve the single objective UPFC placement problems to find the appropriate membership function for each objective in proposed multi-objective optimization method as explained in subsections VI.2.1 and VI.2.2.

3. For each solution generated by PSOTVAC/BFA algorithm perform the following steps.

3.1. For each solution, the location and magnitude of the series voltage and parallel reactive current is available. Calculate the installation cost of UPFC for each solution with the method explained in subsection VI.1 and find the installation cost of UPFC at the end of the planning time horizon considering the interest rate.

3.2. Run an OPF for each load level in each year and calculate the generation and congestion costs, and maximum voltage deviation for the peak load of each year. Calculate the total reduction in generation and congestion cost and improvement in voltage deviation comparing to the results obtained in step 1.

3.3. Find the value of fitness (the value of objective function is explained later in VI.2.3) for this solution.

4. Update the population gradually and find the best solution of the problem using the PSOTVAC/BFA algorithm presented in subsection III.3.

III. BASIC MODELING CONCEPTS

III.1. Static Model of UPFC

This sub-section presents a method for incorporating UPFC in OPF problem. The power Injection model has been proposed and widely used in literature in order to model the UPFC in static studies [4]. The modeling proposed here does not change the existing admittance matrix, and so its implementation in power flow and OPF algorithms is easier comparing to the other models. This is the main advantage of this model.

As shown in Fig. 2, the status of the UPFC can be determined from the series inserted voltage ( ) and active and reactive component of shunt branch of UPFC (and). Therefore the UPFC has four controllable parameters, magnitude of series voltage , which is in series with the transmission line, phase angle of this voltage , and reactive and active components of the shunt transformer current and [14].

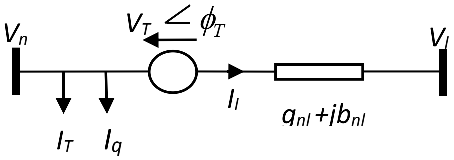

Fig. 2. UPFC static equivalent circuit

It should be noted that the shunt branch of UPFC can be fed by an external active power source but practically this external source does not exist, so the active component of the shunt transformer current ( ) can be omitted from the list of UPFC controllable parameters and it has only three controllable parameters in this model, which are limited as (1):

$$\begin{aligned} V_T^{Min} &\le V_T \le V_T^{Max} \\ \phi_T^{Min} &\le \phi_T \le \phi_T^{Max} \\ I_q^{Min} &\le I_q \le I_q^{Max} \end{aligned} \tag{1}$$

Therefore in this paper, for the OPF analysis, the optimization method should find the optimal UPFC parameters V_T, ϕ_T , and I_q. Equation (2) represents the apparent power sent from bus n to l and vice versa.

$$\begin{aligned} S_{nl} &= P_{nl} + jQ_{nl} = V_n I_{nl}^* = V_n (I_T + I_q + I_l)^* \\ S_{ln} &= P_{ln} + jQ_{ln} = V_l I_{ln}^* = V_l (-I_l)^* \end{aligned} \tag{2}$$

According to (2) the active and reactive component of these apparent powers can be found using (3) and (4). Now the final model of this device in OPF study should be developed considering the above relationships. Fig. 3 shows the final model of the UPFC and regarding transmission line. As can be seen in this figure the UPFC is modeled as two power sources. The active and reactive power components of these sources are extracted from (3) and (4). For the sake of completeness the active and reactive power of the sources can be found directly using (5) and (6) based on [14]-[16]. This model can be incorporated in an appropriate OPF algorithm as a subroutine of the placement and sizing program.

$$\begin{aligned} P_{nl} &= (V_n^2 + V_T^2) g_{nl} + 2 V_n V_T g_{nl} cos(\phi_T - \delta_{nl}) - V_n V_T (g_{nl} \cos\phi_T + b_{nl} \sin\phi_T) \\ &\quad - V_n V_l (g_{nl} \cos\delta_{nl} + b_{nl} \sin\delta_{nl}) \\ P_{ln} &= V_n^2 g_{nl} - V_l V_T (g_{nl} cos\phi_T - b_{nl} \sin\phi_T) - V_n V_l (g_{nl} \cos\delta_{nl} - b_{nl} \sin\delta_{nl}) \end{aligned} \tag{3}$$

$$Q_{nl} = -V_n V_T (g_{nl}\sin(\phi_T - \delta_{nl}) + b_{nl}\cos(\phi_T - \delta_{nl})) - V_n^2 b_{ij} - V_n I_q - V_n V_l (g_{nl}\sin\delta_{nl} - b_{nl}\cos\delta_{nl})$$
$$Q_{ln} = -V_l^2 b_{nl} - V_l V_T (g_{nl}\sin\phi_T - b_{nl}\cos\phi_T + V_n V_l (g_{nl}\sin\delta_{nl} + b_{nl}\cos\delta_{nl}))$$
(4)

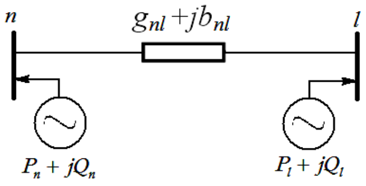

Fig. 3. UPFC power injection model.

$$P_n = -V_T^2 g_{nl} + V_n V_l (g_{nl}\cos\phi_T + b_{nl}\sin\phi_T - 2g_{nl}\cos(\phi_T - \delta_{nl}))$$
$$P_l = V_T V_l (g_{nl}\cos\phi_T - b_{nl}\sin\phi_T)$$
(5)

$$Q_n = V_n I_q + V_n V_l (g_{nl}\sin(\phi_T - \delta_{nl}) + b_{nl}\sin\phi_T)$$
$$Q_l = -V_T V_l (g_{nl}\sin\phi_T + b_{nl}\cos\phi_T)$$

(6)

Iii.2. Long-term load model

The Load Duration Curve (LDC) is an arrangement of all load levels in a descending order of magnitude. In most of planning problems the LDC is used as the long-term model of the system load. The area under the LDC represents the energy demanded by the system. Fig. 4 shows this LDC for IEEE RTS which is used as an illustrative example in section V. This figure also depicts the approximation of annual LDC that is modeled as multiple load blocks. Hours with approximately similar loads are shown in a same load block. The number of blocks that is necessary depends on the accuracy needed. In this figure is the duration of load block b (yr).

The planning horizon is usually more than one year, so in order to model the load in this period we need the peak load and energy growth rates to approximate the LDC of the incoming years. Future annual peak load and energy demand growths are equal to the base year values times the regarding growth rates. The annual LDCs for the next years can be found using the method presented in [17]. A generalized LDC can be found aggregating the LDCs of the years of the planning time horizon, in a descending order of magnitude of load blocks. The blocks with near load magnitudes can be merged to reduce the computational burden of the large number of load levels. But in our formulation such a generalized LDC cannot be used since the economic model presented in section IV considers the interest rate.

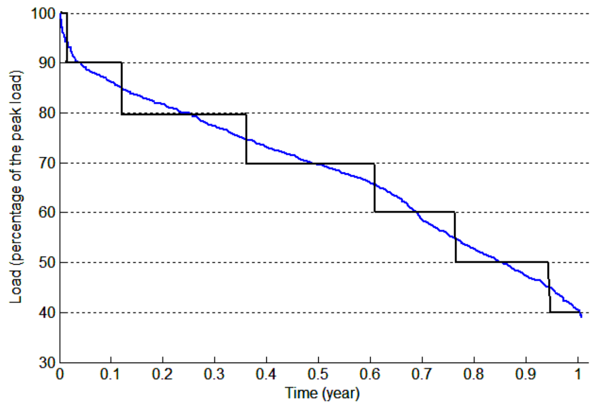

Fig.4 Load duration curve.

Iii.3. Hybrid psotvac/bfa

• Classic PSO

Classic PSO (CPSO) is one of the optimization techniques and a kind of evolutionary computation technique which is launched by the Aberhart Rasel. The method has been found to be robust in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality through adaptation, which is derived from the social-psychological theory. The features of the method are as follows [6]:

- The method is developed from research on swarm such as fish schooling and bird flocking.

- It is based on a simple concept. Therefore, the computation time is short and requires few memories [5].

- It was originally developed for nonlinear optimization problems with continuous variables. It is easily expanded to treat a problem with discrete variables.

CPSO is basically improved through simulation of bird flocking in two-dimension space. The position of each agent is defined by XY axis position and also the velocity is expressed by VX (the velocity of X axis) and VY (the velocity of Y axis). Modification of the agent position is notified by the position and velocity information . Bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. This information is comparison of personal experiences of each agent. Moreover, each agent knows the best amount so far in the group (gbest) among pbest. This information is comparison of knowledge of how the other agents around them have performed. Namely, each agent tries to update its position using the following information:

- The current positions (x, y),

- The current velocities (VX, VY),

- The distance between the current position and pbest

- The distance between the current position and gbest

This modification can be represented by the concept of velocity and the place of particle. Velocity of each agent can be modified by the following equation:

$$x_i(t+1) = x_i(t) + v_i(t+1)$$
(7)

$$V_i(t+1) = \omega v_i(t) + c_1 r_1(t)[pbest_i(t) - x_i(t)]$$
(8)

Where,

- xi: position of agent i at iteration k
- vi: velocity of agent i at iteration k
- w: inertia weighting
- c1,2: tilt coefficient
- r1,2: rand random number between 0 and 1
- leader: archive of unconquerable particles
- pbesti: pbest of agent i
- gbest: gbest of the group

Convergence of the PSO strongly depended on w, c1 and c2. While c1,2 are between 1.5 till 2, however the best choice to these factors is 2.05. Also, 0≤w<1; this value is really an important factor to the system convergence and it is better that this factor is defined dynamically. It should be between 0.2 and 0.9 and should decrease linear through evolution process of population. Being extra value of w at first, provides appropriate answers and small value of that help the algorithm to convergence at the end.

• PSO with Time-Varying Inertia Weight

The PSOTVIW method is capable of locating a good solution at a significantly faster rate, when compared with other meta-heuristic techniques; its ability to fine tune the optimum solution is comparatively weak, mainly due to the lack of diversity at the end of the search. Also, in PSO, problem-based tuning of parameters is a key factor to find the optimum solution accurately and efficiently. The main concept of PSOTVIW is similar to CPSO in which the Eqs. (7), (8) are used. However, for PSOTVIW the velocity update equation is modified by the constriction factor C and the inertia weight w is linearly decreasing as iteration grows.

$$V_i(t+1) = C\{\omega v_i(t) + c_1 r_1(t)[pbest_i(t) - x_i(t)]$$

$$+ c_2 r_2(t)[leader_i(t) - x_i(t)]\} \quad (9)$$

$$\omega = (\omega_{max} - \omega_{min}).\frac{(k_{max} - k)}{k_{max}} + \omega_{min} \quad (10)$$

$$C = \frac{2}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|}, where\, 4.1 \le \phi \le 4.2 \quad (11)$$

PSO with Time-Varying Acceleration Coefficients (PSO-TVAC)

Consequently, PSO-TVAC is extended from the PSO-TVIW. All coefficients including inertia weight and acceleration coefficients are varied with iterations. The equation of PSO-TVAC for velocity updating can be expressed as:

$$V_i(t+1) = C\{\omega v_i(t) + ((c_{1f} - c_{1i})\frac{k}{k_{max}} + c_{1i}).r_1(t)[pbest_i(t) - x_i(t)]$$

$$+((c_{2f} - c_{2i})\frac{k}{k_{max}} + c_{2i}).r_2(t)[leader_i(t) - x_i(t)]\}$$
(12)

• Bacteria Foraging Algorithm

Bacteria Foraging Algorithm (BFA) is one of the new optimization techniques which is based on the assumption that animals search for nutrients which maximizes their energy intake (E) per unit time (T) spent for foraging [8]. The E.coli bacterium is probably the best understood micro organism. Generally the bacteria move for a longer distance in a friendly environment.

CHEMO-TACTIC BEHAVIOR OF ESCHERICHIA COLI

We consider the foraging behavior of E. coli, which is a common type of bacteria. Its behavior and movement comes from a set of six rigid spinning (100–200 r.p.s) flagella, each driven as a biological motor. The E. coli bacterium alternates through running and tumbling. Running speed is 10–25 body lengths per second, however they can’t swim straight. The bacterium sometimes tumbles after a tumble or tumbles after a run [8]. This alternation between the two modes will move the bacterium, and this enables it to "search" for nutrients. If θi(j,k,l) represent the position of the each member in the population of S bacterial at the jth chemotactic step, and kth reproduction step, and lth elimination, the movement of bacterium may be presented by:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\varphi(j) \quad (13)$$

Where, C(i)(i = 1,2,…, S) is the size of the step taken in the random direction specified by the tumble. ϕ(j) is the random direction of movement after a tumble and J(i, j, k, l) is the fitness, which also denote the cost at the location of the ith bacterium θi(j, k, l) € Rn. Also if at θi (j + 1, k, l) the cost J(i, j + 1, k, l) is better (lower) than at θi (j, k, l) , then another step of size C(i) in this same direction will be taken. Otherwise, bacteria will tumble via taking another step of size C (i) in random direction ϕ (j) in order to seek better nutrient environment.

SWARMING

An interesting group behavior has been observed for several motile species of bacteria including E.coli and S. typhimurium [8]. To achieve the function to model the cell-to-cell signaling with an attractant and a repellant. The E.coli swarming mathematical equation can be represented by:

$$J_{cc}(\theta,P(j,k,l))=\sum_{i=1}^{s}J_{cc}^{i}(\theta,\theta^{i}(j,k,l))$$

$$=\sum_{i=1}^{s}\left[-d_{attract}\exp(-\omega_{attract}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2)\right]$$

$$+\sum_{i=1}^{s}\left[-h_{repellant}\exp(-\omega_{repellant}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2)\right]$$

(14)

The $J_{cc}(\theta,P(j,k,l))$ is the additional cost function added to the actual objective function (for minimization) to present a time varying objective function. The additional cost function $J_{cc}(\theta,P(j,k,l))$ for each bacterium is composed of S terms $J_{cc}^{i}(\theta,\theta^{i}(j,k,l))$ measuring attracting and repelling effects between two bacteria θ and θ^i , illustrated in the next two lines of (12), respectively. In the original version of BF proposed by Passino [8], the parameters of dattract, ωattract, hrepelent and ωrepelent are set as follows:

ωattract=0.2, ωrepelent=10, dattract=hrepelent (15)

Considering the above parameters, each bacterium will try to move toward other bacteria to decrease the additional cost function $J_{cc}(\theta,P(j,k,l))$, but not too close to them, which is called swarming effect enhancing the local search capability of BFA. More details about (14) can be found in [8].

S = total number of bacteria

p = number of parameters to be optimized which are present in each bacterium

θ= [θ1, θ2,…, θp]T is a point in the p-dimensional search domain

dattract = depth of the attractant released by the cell

wattract = measure of the width of the attractant signal

hrepellant=dattract = height of the repellant effect

wrepellant = measure of the width of the repellant

REPRODUCTION

According to the rules of evolution, individual will reproduce themselves in appropriate conditions in a certain way. For bacterial, a reproduction step takes place after all chemotactic steps.

$$J_{health}^{i}=\sum_{j=1}^{N_c+1}J(i,j,k,l)$$

(16)

Where,

Jihealth = health of bacterium i

For keep a constant population size, bacteria with the highest Jhealth values die. The remaining bacteria are allowed to split into two bacteria in the same place. Actually, in the reproduction loop only the poor individuals, which are unlikely to represent promising areas of the solution space, are filtered out and replaced by good solutions. In other words, the reproduction loop prevents wasting the search ability of BFA for searching non-promising areas of the solution space and thus the algorithm can concentrate on the promising areas of the solution space and search these areas with high accuracy and resolution. This characteristic leads to high local search ability of BFA. Moreover, different search paths are devised for the bacteria generated from the same individual in the next iterations of the loop, due to the chemotaxis operators, such as tumble and swim. In other words, the bacteria generated from the same individual will only be the same at the birth place, but will proceed in different directions and search the solution space through different paths. Consequently, the reproduction loop will not deteriorate the search diversity of BFA but can effectively enhance its search efficiency by filtering out poor individuals of the population and concentrating on the promising areas of the solution space.

ELIMINATION-DISPERSAL

In evolutionary process, elimination and dispersal events can occur such that bacteria in a region are killed or a group is dispersed into a new part of the environment due to some influence. They have the effect of possibly destroying chemotactic progress, but they also have the effect of assisting in chemotaxis, since dispersal may place bacteria near good food sources. From the evolutionary point of view, elimination and dispersal was used to guarantees diversity of individuals and to strengthen the ability of global optimization [8]. In this technique to keeping the number of bacteria in the population constant, if a bacterium is eliminated, simply disperse one to a random location on the optimization domain [19].

• Hybrid PSOTVAC-BFA

The main goal of the proposed hybrid PSOTVAC/BFA is to find the minimum of the function presented in equation (2). Actually, PSOTVAC is characterized as a simple, easy to implement and computationally efficient method, which is flexible with high global exploration ability. However, the local search ability of this algorithm is not as high as its global search ability and premature convergence may be occurred for the algorithm. In the opposite, the BFA algorithm via its adaptive reproduction and chemotaxis loop can effectively search promising areas of the solution space with high resolution enhancing the local search capability of PSOTVAC. However, there are some drawbacks in BFA in terms of its complexity and possibility to be locked up by a local solution. The proposed PSOTVAC can overcome these problems. Therefore, the algorithms have been combined such that each algorithm covers the deficiencies of the other one. The obtained hybrid method is designated as the hybrid PSOTVAC/BFA. The steps for executing the proposed hybrid method are:

STEP 1: Execute PSOTVAC as described.

STEP2: Transport the solution obtained from the PSOTVAC to the BFA as an initial solution. The other initial individuals of the BFA are generated randomly within the allowable ranges.

STEP3: Execute BFA as described.

STEP4: Step 2 is run in the inverse direction such that the solution obtained by the BFA is transferred to the PSOTVAC and the initial population of the PSOTVAC is constructed.

STEP5: Repeat steps 1-4 until the termination criterion is satisfied. Here, the termination criterion is set as the maximum number of iterations of the cycle 1-4.

Iv. Proposed multi-objective method

Ref [18] reviews various AI based optimization methods used for the placement and coordination of FACTS controllers. Because of the high investment cost of UPFC, there is a considerable risk in its application. Therefore, especial cares should be taken in locating and parameter setting of this controller. The aim of operation and planning in deregulated power systems is to maximize the social welfare through minimization of the costs of the system, while the electric power should be delivered to the customers with sufficient quality and reliability. The objectives of this study are system cost minimization, congestion minimization, and voltage profile improvement, through proper application of UPFC.

IV.1. Installation Cost of UPFC

The cost of UPFC depends on the rated capacity of its convertors. Based on the new researches in this area [20], for each convertor the installation cost can be calculated using (17). Where IC and S are the installation cost in US Dollar and rated capacity of the convertor in MVA respectively.

$$IC = S \times (0.3S^2 + 269.1S + 188220) \tag{17}$$

The above formulation of UPFC cost seems very simple and straightforward at the first sight, but it is not suitable to be applied along with power injection model of UPFC. This problem should be solved before continuing further. UPFC includes two convertors, one of those is in series with the transmission line and the other is the parallel convertor. It is obvious that installation of UPFC should not affect the rated current capacity of the transmission line and rated voltage of the installation bus of the UPFC. Therefore the rated capacity of the series and parallel convertor depend on the maximum injected series voltage (since the maximum current is equal to the maximum current capacity of the line) and maximum reactive current of the parallel branch (since the maximum bearable voltage should be equal to the maximum voltage of the bus as a result of insulation coordination) respectively. It means that the total installation cost increase monotonically with increase in magnitude of the series voltage and parallel reactive current.

In subsection V.2.1 where the total revenue is modeled, the interest rate is also considered in installation cost of UPFC to find a more realistic model for investment recovery.

Iv.2. Objective Fuzzification

In Fuzzy multi-objective optimization domain each objective is associated with a membership function, which specifies the degree of satisfaction of this objective. Fuzzy sets consider varying degrees of membership function values for each objective from zero to unity [13]. On the contrary in the crisp domain, the objective is either satisfied or violated, indicating membership values of unity and zero, respectively.

As our problem is a multi-objective optimization problem, it is necessary to determine the membership functions of each objective. The present work considers the following objectives for the UPFC placement problem.

1. Maximization of total revenue at the end of planning time horizon.

2. Minimization of voltage magnitude deviation over all of the network buses.

The membership function for each objective consists of a lower and an upper bound value together with a strictly monotonically decreasing and continuous function of this objective and is described as follows.

IV.2.1. Membership Function of Total Revenue

In order to find the total generation and congestion cost for each case, first an OPF is performed for each load level. The power injection model (subsection II.1) is used to incorporate UPFC in OPF problem. The formulation of OPF problem has been presented in so many papers such as [21] and it is not repeated here for the sake of conciseness. The total revenue due to application of UPFC in a transmission system is given in (8). Where IC_p , IC_{se} , and N_{yr} are the installation cost of parallel and series convertors, the interest rate and number of years in planning time horizon, respectively.

$$TR = -(IC_p + IC_{se}) \times (1+r)^{N_{yr}} + \sum_{yr=1}^{N_{yr}} \sum_{b=1}^{N_{b,yr}} [\rho_{b,yr} .(GCR_{b,yr} + CCR_{b,yr}) \times (1+r)^{[N_{yr} - yr + 1]}] \tag{18}$$

$CCR_{b,yr}$	Reduction in congestion cost in load block *b* and year *yr* (\$/hr).
$GCR_{b,yr}$	Reduction in generation cost in load block *b* and year *yr* (\$/hr).
IC_p	Installation cost of parallel convertors (\$).
IC_{se}	Installation cost of series convertors (\$).
N_{yr}	Number of years in planning time horizon.
$N_{b,yr}$	Number of load blocks in *yr*.
r	Interest rate.
$\rho_{b,yr}$	Duration of load block *b* in year *yr* (hr).

Congestion cost can be calculated as follows.

$$CC = \sum_{l=1}^{N_l} \Delta\lambda_l . P_l \tag{19}$$

$$\Delta\lambda_l = |LMP_i - LMP_j| \tag{20}$$

Where, i and j are the sending and receiving end of line l, respectively.   is the power transferred by this line and is the Locational Marginal Price at bus i.

Considering a positive revenue for application of UPFC,

$$\frac{(IC_p + IC_{se}) \times (1+r)^{N_{yr}}}{\sum_{yr=1}^{N_{yr}} \sum_{b=1}^{N_{b,yr}} [\rho_{b,yr} .(GCR_{b,yr} + CCR_{b,yr}) \times (1+r)^{[N_{yr} - yr + 1]}]} \le 1 \tag{21}$$

Let us define

$$x = \frac{(IC_p + IC_{se}) \times (1+r)^{N_{yr}}}{\sum_{yr=1}^{N_{yr}} \sum_{b=1}^{N_{b,yr}} [\rho_{b,yr} .(GCR_{b,yr} + CCR_{b,yr}) \times (1+r)^{[N_{yr} - yr + 1]}]} \tag{22}$$

As can be seen in (22) if x is high, the total revenue is low and if x is low, then the total revenue is high. Membership function for the net saving (profit) is given in Fig. 5. According to (21) $x_{\max}$ is assumed to be 1.0. In order to find $x_{\min}$ the proposed method is once applied on the single objective problem without considering the voltage improvement as one of the objectives. In fact the problem should be solved to maximize the total revenue and the value of $x_{\min}$ should be found using the optimum solution of this single objective problem. The value of $x_{\min}$ is determined based on the maximum profit to cost ratio. Based on these assumptions:

$$\mu_x = \begin{cases} 1 & if \;\; x \le x_{\min} \\ \dfrac{(x_{\max} - x)}{(x_{\max} - x_{\min})} & if \;\; x_{\min} \le x \le x_{\max} \\ 0 & if \;\; x_{\max} \le x \end{cases} \tag{23}$$

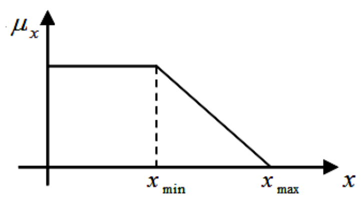

Fig. 5. Membership function of saving.

IV.2.2. Membership Function for Voltage Deviation

The Voltage deviation of buses should be minimized.

$$z_{b,yr} = \min_i(|V^n - V_{i,b}, yr|) \tag{24}$$

Where, $V_{i,b,yr}$ is the voltage magnitude at node i for bth load level of year yr in p.u., and   is the nominal voltage magnitude which is equal to one p.u. The less the maximum value of nodes voltage deviation, the higher the assigned membership value and vice versa. Fig. 6 shows the membership function for voltage deviation defined in (24). Based on Fig. 6 and considering as a constraint of OPF problem:

$$\mu_z = \begin{cases} 1 & if \;\; 0 \le z \le z_{\min} \\ \dfrac{(z_{\max} - z)}{(z_{\max} - z_{\min})} & if \;\; z_{\min} \le z \le z_{\max} \\ 0 & if \;\; z_{\max} \le z \end{cases} \tag{25}$$

In this study, $z_{\min}$ and $z_{\max}$ are considered to be 0.05 and 0.10, respectively. V_n =1 and $z_{\min}$ = 0.05 mean that if the system voltage falls between 0.95 and 1.05 p.u. the membership value will be one. Regarding to the situation where the voltage deviation is fully satisfied as one of the objectives.

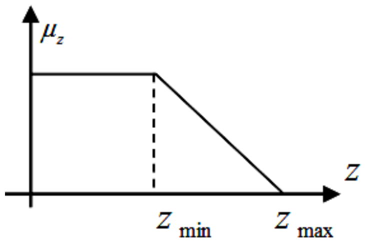

Fig. 6. Membership function of voltage deviation.

IV.3. Multi-Objective Formulation

In previous subsection two fuzzified objectives were described. This subsection integrates them into a fuzzy satisfaction objective function as (26).

$$\max \qquad F = \mu_x + \frac{\sum_{yr=1}^{N_{yr}} \mu_{z_{peak,yr}}}{N_{yr}} \qquad (26)$$

It is important to note that the improvement of the voltage profile in peak load levels, also leads to the improvement in lower load levels.

V. CASE STUDIES

In order to test the effectiveness of the proposed method, IEEE Reliability Test System including 24 bus, 26 generators, 34 lines and 4 transformers is chosen. A time horizon of 3 years is considered for the study and the interest rate is 0.05.

Table I: Generation Data

Unit Type	a ($/(MWh)2)	b ($/MWh)	c ($/h)	p_g^{min} (MW)	p_g^{max} (MW)
U12	0.08	38.9	56	2	12
U20	0.44	48.4	633	16	20
U50	0	2.3	10	10	50
U76	0.01	11	145	15	76
U100	0.07	25.4	615	25	100
U155	0.01	9.3	220	54	155
U197	0.02	28.5	739	69	197
U350	0.01	8.6	440	140	350
U400	0	13.5	621	100	400

TABLE II: LOAD DATA

Bus No	Pd (MW)	Qd (MVAR)	Bus No	Pd (MW)	Qd (MVAR)
1	108	22	10	195	40
2	97	20	13	265	54
3	180	37	14	194	39
4	74	15	15	317	64
5	71	14	16	100	20
6	136	28	18	333	68
7	125	25	19	181	37
8	171	35	20	128	26
9	175	36			

Table III: Psotvac/Bfa Algorithms' Parameters

PSO-TVAC	C1f	0.2
	C1i	2.5
	C2f	2.5
	C2i	0.2
	ϕ	4.1
	wmin	0.4
	wmax	0.9
	Population	40
	Iteration	100
BFA	D	4
	S	40
	Nc	20
	NS	4
	Nre	4
	Ned	2
	Ped	0.25
	c	0.007

V.1. Base Case, without UPFC

As explained in section II in order to find the revenue obtained by UPFC placement, the total generation cost and total congestion cost for the base case should be determined. Firstly the generation and congestion costs should be found for each load level. For the sake of conciseness only results of the peak load level during the first year are shown in table IV.

Table IV: Summary of Opf Results for Peak Load of the First Year

Generation cost	Congested lines	Maximum flow limit of line	Congestion cost	Voltage deviation
60953.625	7-8	175	14536	0.098
	11-13	175		

Table V: Summary of base case results

Average Generation cost ($/hr)	Average Congestion cost ($/hr)	Average Voltage deviation
419954.1	9645.5	0.0993

The average generation cost (per hour) and the average voltage deviation are presented in Table V. In order to calculate the voltage deviation in each load level (8) is employed. The voltage deviation reported in Table V is the average value in peak load level of all years. As can be seen in Table V, the average generation cost is very high for the base case as a result of non-converged OPF for some of load levels. The OPF is not converged for peak load level of the second and third years and as a result, the average generation cost is a little high.

V.2. Revenue Maximization as the Objective Function

As mentioned in section II, before applying the proposed multi-objective method, the single objective problem should be solved to find the maximum attainable revenue. This is necessary for the construction of membership functions in the multi-objective problem. Moreover, the results of this single objective problem can be compared with those obtained for multi-objective problem to find out how the revenue changes. Table VI shows the optimal solution of this single objective problem. 3 optimal solutions with higher values of revenue are ranked in this table. In order to find the second ranked solution, the location of UPFC for the first solution is forbidden for UPFC installation and the problem is solved again. The size of parallel and series converters is also presented in this table. Table VII shows a summary of the results of this case from the economic point of view, such as installation cost of UPFC for each solution and total revenue and Benefit Cost Ratio (BCR). It should be noted that in Table VII the costs and benefits are given at the end of time horizon considering the interest rate. The comparison between the solutions of the single- and multi-objective problems is presented in V.3.

Table VI: Top Ranking optimal solutions of case vi.2

Rank	Line	V_T (p.u.)	I_q (p.u.)	ϕ_T (Rad)	Voltage deviation
1	18-21	0.1936	0.5665	2.61	0.0712
2	16-17	0.1812	0.6540	2.85	0.0680
3	20-23	0.1817	0.8901	3.05	0.0751

Table VII: Summary of the results of case vi.2

	S_p (MVA)	S_{se} (MVA)	IC (106 $)	GCR (106 $)	CCR (106 $)	BCR
1	56.65	96.80	38.12	157.68	25.28	6.56
2	65.40	90.60	38.63	125.92	23.45	5.47
3	89.01	90.85	45.25	110.38	19.03	4.31

V.3. Multi-Objective problem

The multi-objective problem is solved in this section. Three top ranking solutions are reported in Table VIII. A summary of the results of this case is presented in Table IX. It should be noted that the top ranked solution is even different from all the tap ranked solutions of the single objective problem presented in Table VI (both location and parameters). It is quite usual for multi-objective optimization algorithms to make a compromise between the objectives. As can be seen in this table the voltage deviation is improved but the value of BCR is lower for the best solution of Table IX comparing with the results of table VII.

The results also show that the investment recovery is guaranteed in this case since the revenue is still very high. The high value of BCR justifies the investment comparing to the other investment opportunities.

Table VIII: Top ranking optimal solutions of case vi.2

Rank	Line	V_T (p.u.)	I_q (p.u.)	ϕ_T (Rad)	Voltage deviation
1	14-16	0.1824	0.8053	3.53	0.0452
2	16-17	0.1705	0.8141	3.78	0.0468
3	20-23	0.1718	0.9032	2.75	0.0501

Table IX: Summary of the results of case vi.2

	S_p (MVA)	S_{se} (MVA)	IC (106 $)	GCR (106 $)	CCR (106 $)	BCR
1	80.53	91.20	40.89	136.63	20.28	4.84
2	81.41	85.25	39.50	116.83	22.51	4.53
3	90.32	85.90	42.09	91.27	18.31	3.60

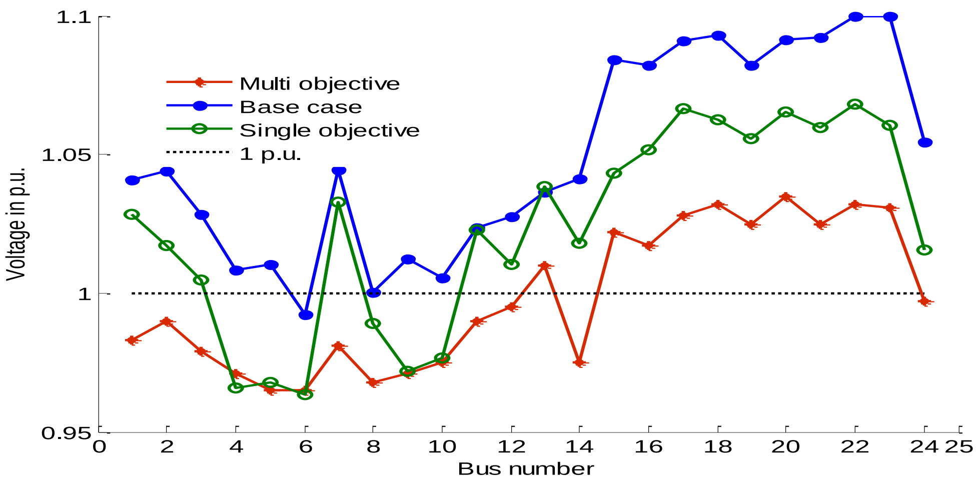

Fig. 7. Voltage profile for different case studies

In order to analyze the improvement of voltage profile after UPFC placement the voltage profile is depicted for the base case and the best solutions of the single objective and multi-objective cases for the peak load of the first year are depicted in Fig. 7. As can be seen in this figure, the single objective optimization has improved the voltage profile to some extent, but this improvement is lower comparing to the improvement achieved by presented multi-objective method.

V.4. Discussion on the discrete nature of the UPFC size

The aim of this paper is introducing a framework for multi-objective long-term planning of UPFC and because of lack of data on commercially available UPFC sizes some aspects of this device are not modeled in this study. Moreover UPFC is not widely used in practical power systems and the ones used have been custom-designed. However this can be introduced to the model easily since heuristic approach has been used and the algorithm can be modified to consider the discrete variables (variables and).

VI. CONCLUSION

A PSOTVAC/BFA-based fuzzy multi-objective optimization methodology has been proposed in this paper for optimal placement and parameter setting of UPFC over a long term planning time horizon. In fuzzifying process the membership functions have been obtained with an effective adaptive method, instead of the predefined membership functions. The results of the second case study (subsection V.2) indicates that ignoring the voltage deviation in UPFC placement problem leads to a high voltage deviation while the BCR is very high. The results of multi-objective problem show that this voltage deviation can be improved while the value of revenue is still high enough. Interest rate is considered and the results show that the proposed method guarantees the investment recovery since the revenue is so much higher than the installation cost. The high value of BCR justifies the investment comparing to the other investment opportunities. Some other aspects of the proposed method are discussed in case studies.

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